CFD Evaluation of Lean-Direct Injection Combustors for Commercial Supersonics Technology

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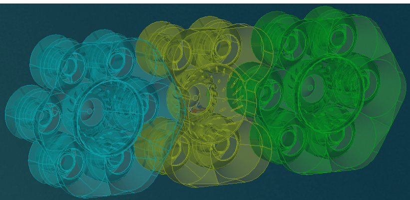
Motivation for Current Work

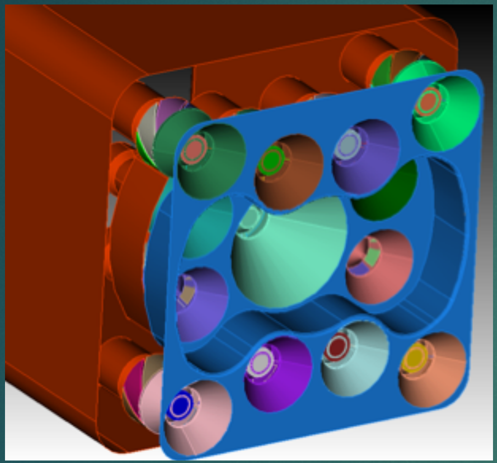
- NASA's Commercial Supersonic Technology (CST) Project Goals:
  - Design a combustor that produces EINOx emissions in the 5-15 range at Supersonic Cruise conditions
  - High temperature combustor liners, Composition controlled fuels
- NASA Glenn Research Center's N+3 Project Focus:
  - Design/Evaluate Lean-Burn/Lean-Dome combustors in partnership with OEMs and injector manufacturers to meet program goals
- Current work: CFD analysis of 2nd and 3rd generation Lean Direct Injection (LDI) flame-tube array for CST Cruise conditions using National Combustion Code (OpenNCC)

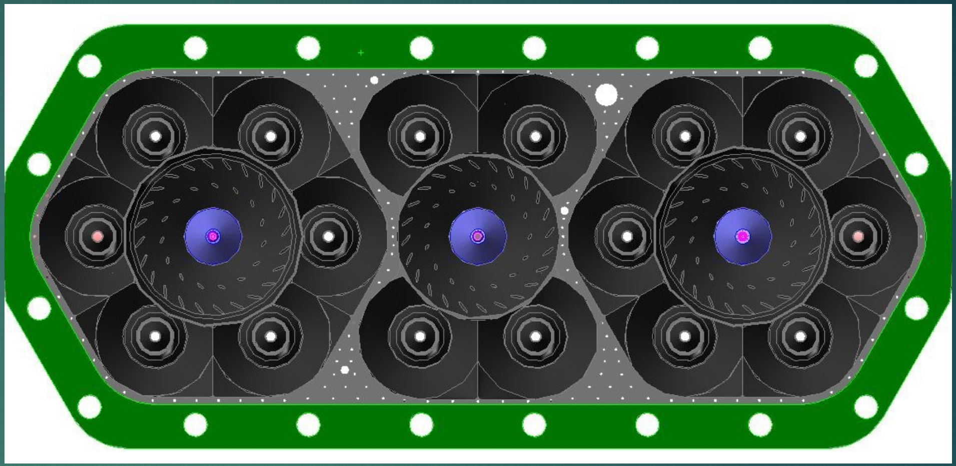
N+2 (LDI-2) vs N+3 (LDI-3) Flametube



N+2 (LDI-2)

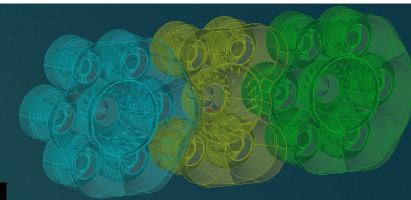
N+3 (LDI-3)

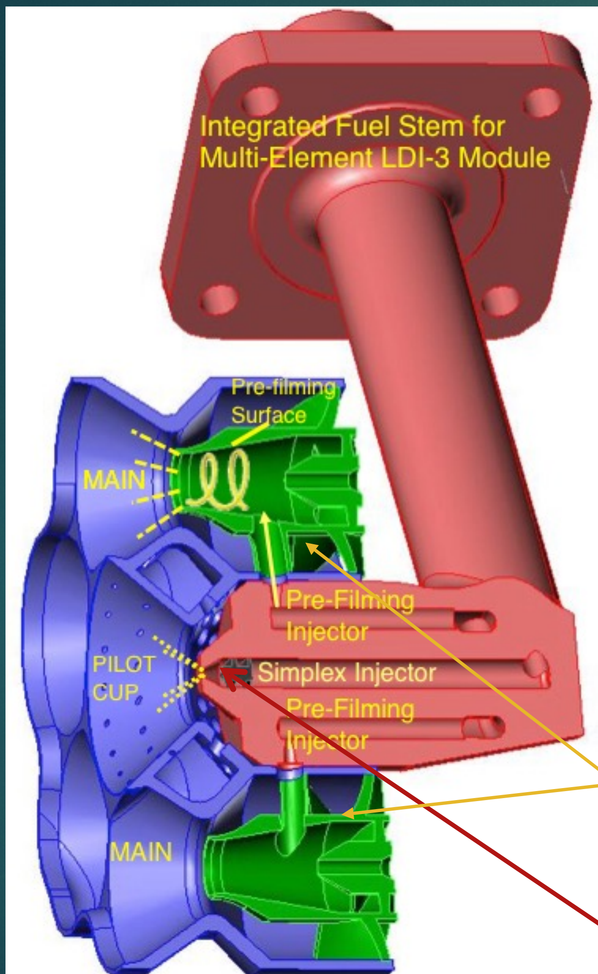


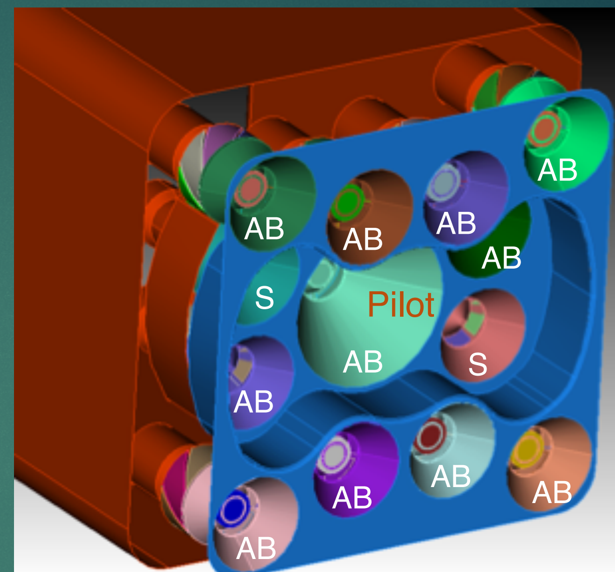


- To accommodate requirements of N+3 combustors as compared to N+2 (smaller core size, lower EINOx) :
    - Denser packaging of injectors at combustor dome face
    - Redesign of Main elements (pre-filming injector)
    - Redesign of Pilot elements air-flow passages
    - Trade low-power operability provided by recess of 'center cup' (N+2) for lower NOx (N+3)?

LDI-2/LDI-3 Pilot/Main Injector Hardware







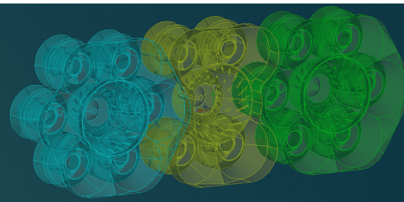
AB = AirBlast
S = Simplex

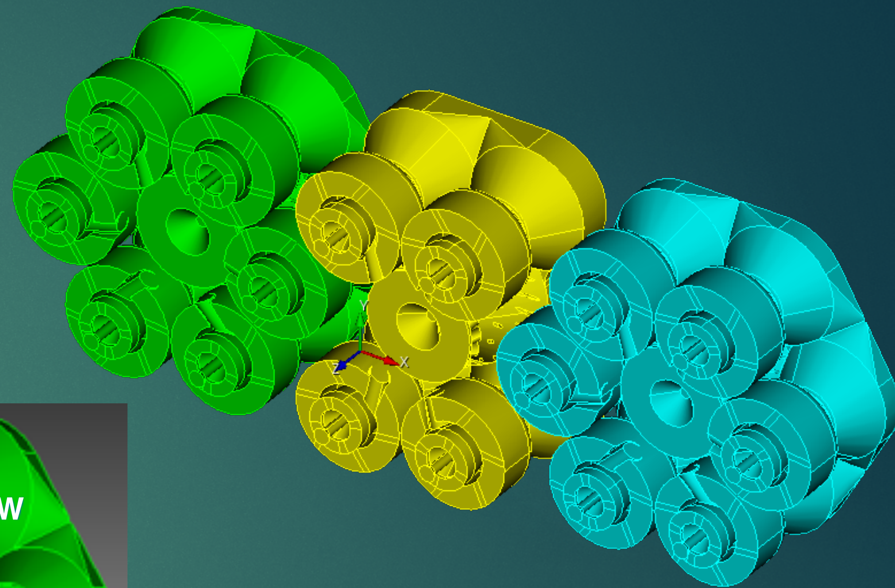
Woodward FST pre-filming injector for <u>*Mains*</u>.
- Fuel injected via plain jet orifice into prefilmer.
- Axial bladed swirlers for air flow

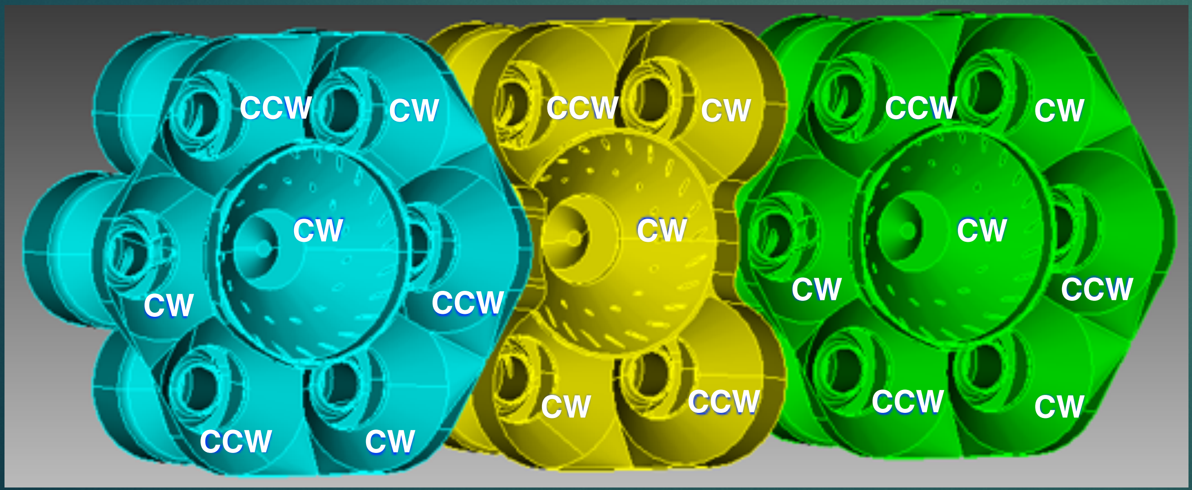
<u>*Pilot*</u> fueled by simplex injector. Circumferential air-flow

OpenNCC analysis provided design-optimization of main/pilot element airflow passages

N+3 Injector Array Setup

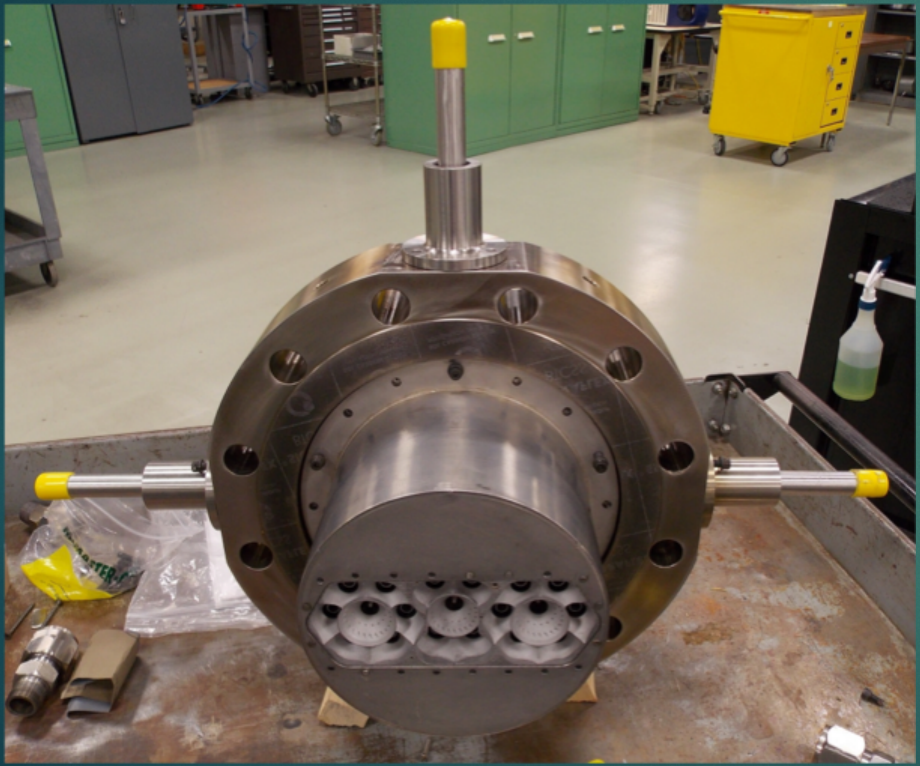


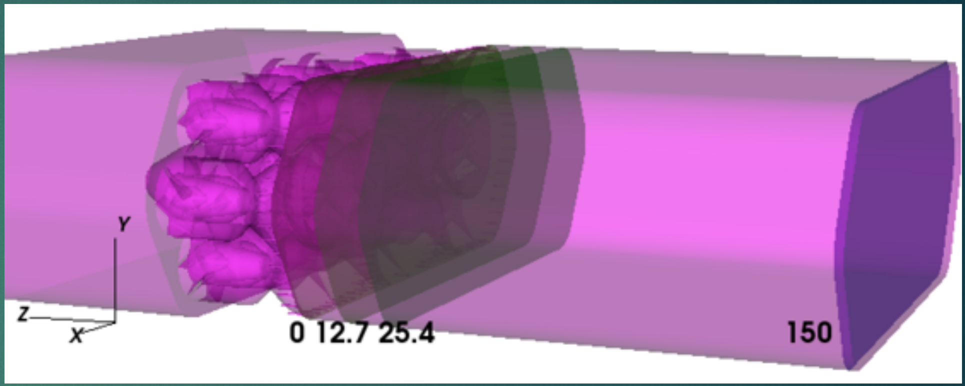


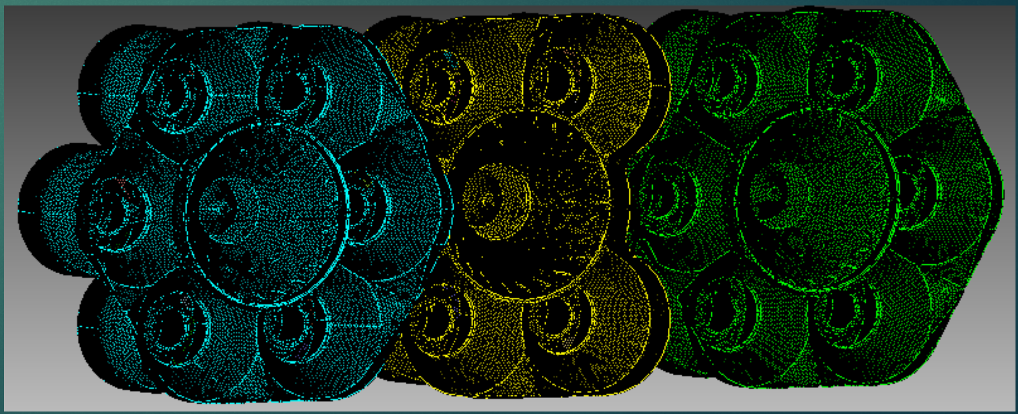


19-Element Module Assembly Flametube Setup for NASA GRC's CE-5 Rig

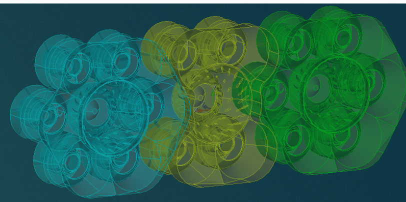
Aft looking Upstream





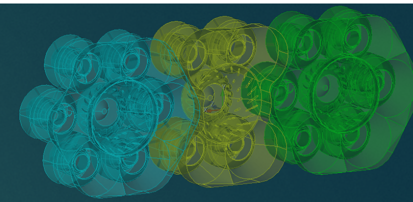


Physical Models for OpenNCC



- Finite volume, 4-stage Runge-Kutta explicit scheme, 2^{nd} order time-accurate
- Time-Filtered Navier-Stokes (TFNS) solver (Liu, Wey AIAA 2014-3569)
- Two-equation, cubic k-ε model with variable C_μ and dynamic wall functions with pressure gradient effects (Shih, NASA TM 2000-209936)
- Reduced-kinetics, finite-rate chemistry. Jet-A fuel modeled as surrogate mixture of decane (73%), benzene(18%), hexane(9%) (14 species, 18 steps)
  - Adiabatic flame temperature, flame-speed, ignition-delay matched with shock-tube data (Kundu, AIAA Paper 2014-3662)
- Lagrangian spray-modeling for liquid fuel droplets (prescribed droplet distribution, injection velocity and direction) (Raju, NASA CR-2012-217294)
- Turbulence-chemistry interaction modeling: Joint Scalar Monte-Carlo PDF solver (Raju, AIAA Paper 2004-0327)

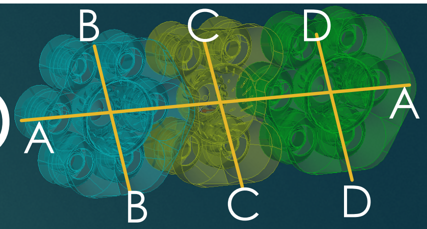
RANS/TFNS Non-Reacting Flow



- P3=1.585MPa, T3=922K, Dp = 5%
- Run 100,000 steps at CFL=0.75 (<1% mass-flow imbalance convergence)
- Fix Ptot, Ttot at Inflow; Fix pressure at Outflow
- Compute ACd from CFD prediction of mass flow rate at each inflow boundary.
  - aggregate of 12 mains (N+2), 16 mains (N+3)
  - single pilot (N+2), three pilots (N+3)
  - pilot cooling and dome cooling (N+3)

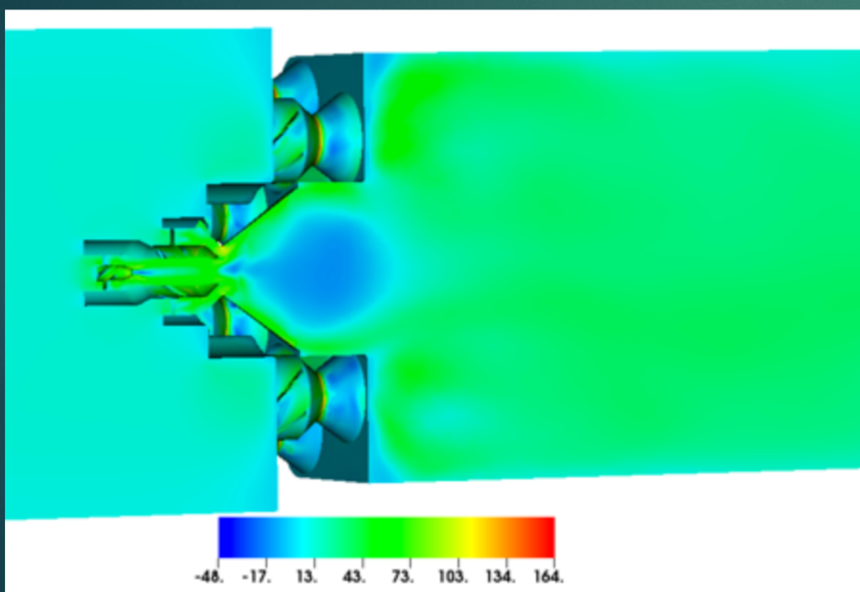
OpenNCC prediction target is for total AC_d to be within 10% of experimental data

Step 1: Non-Reacting Flow CFD

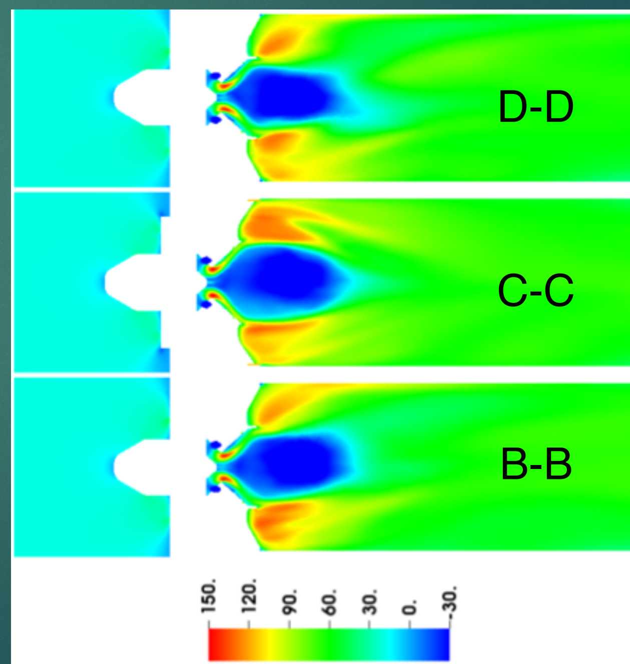


- What are the flow-field differences between the N+2 and N+3 designs at supersonic cruise conditions?

N+2 (Pilot Centerline)



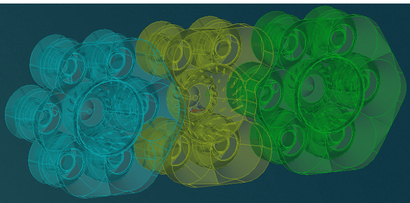
N+3



Step 2: Reacting-Flow OpenNCC

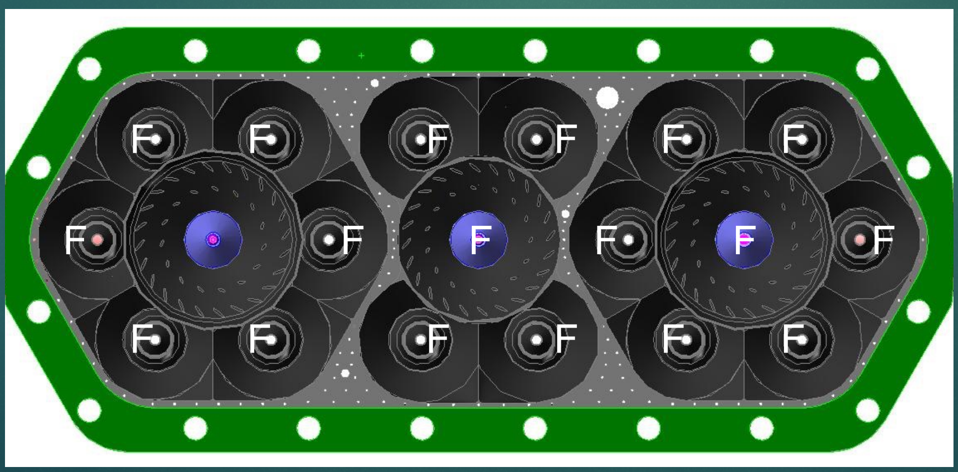
- Use OpenNCC CFD analysis to evaluate mixing, performance and emissions at supersonic cruise conditions (NASA cycle)
  - What are the aerodynamics, flame shapes and emissions characteristics of the two current designs (N+2 and N+3)?
  - What is the impact of varying the liner cooling flow rate on NOx emissions?

CFD Setup for CST Cruise (N+2/N+3)

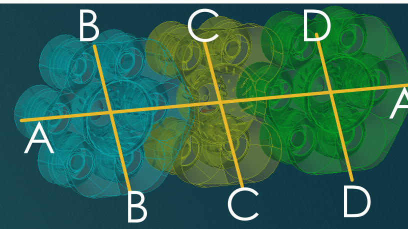


- All Pilots and Mains are fueled at the same equivalence ratio of 0.496 (Fuel/Air ratio = 0.034)
- P_3 = 1.585MPa (230psi), T_3 = 922K (1200F), **D**p = 5%

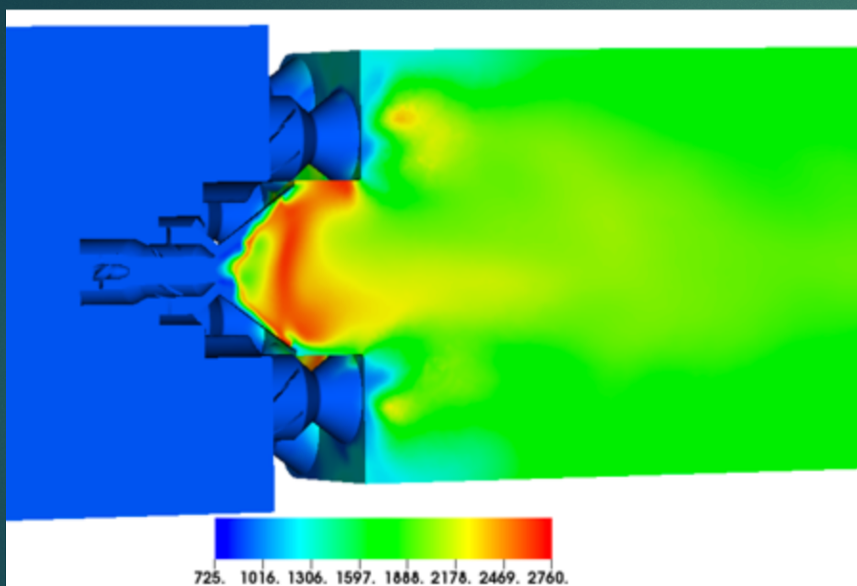
- Typical Subsonic Conditions, for which N+2/N+3 hardware was optimized: P_3 =265psi, T_3 = 811K, Dp = 3%



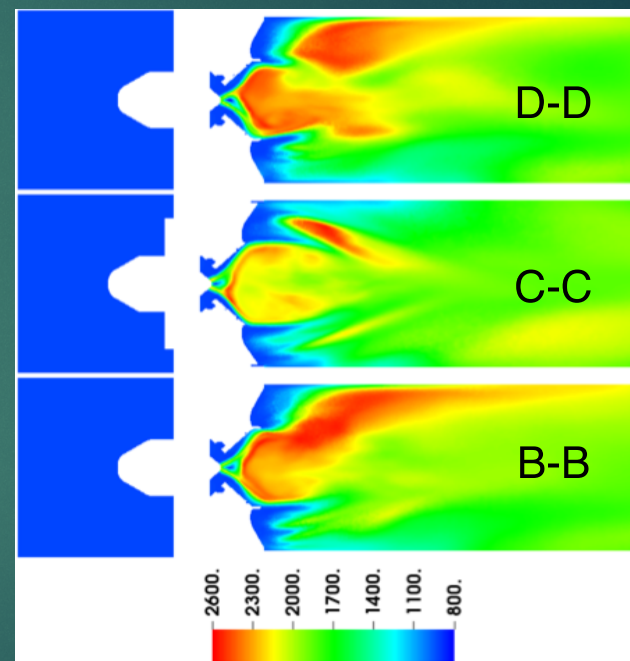
Reacting Flow - Temperature (K) Flametube Centerline: N+2 vs N+3



N+2 (Pilot Centerline)

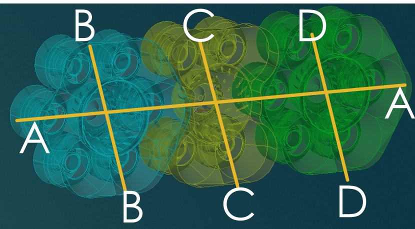


N+3



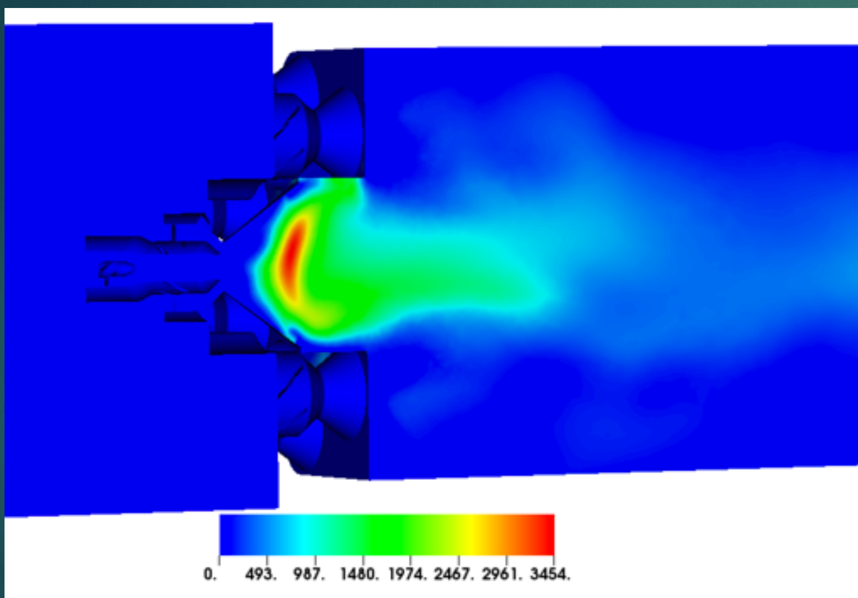
Pilots for N+3 show high temperature 'hot streaks' in combustor downstream of the dome region

Reacting Flow - NO mass-fraction(*1e6) Flametube Centerline: N+2 vs N+3



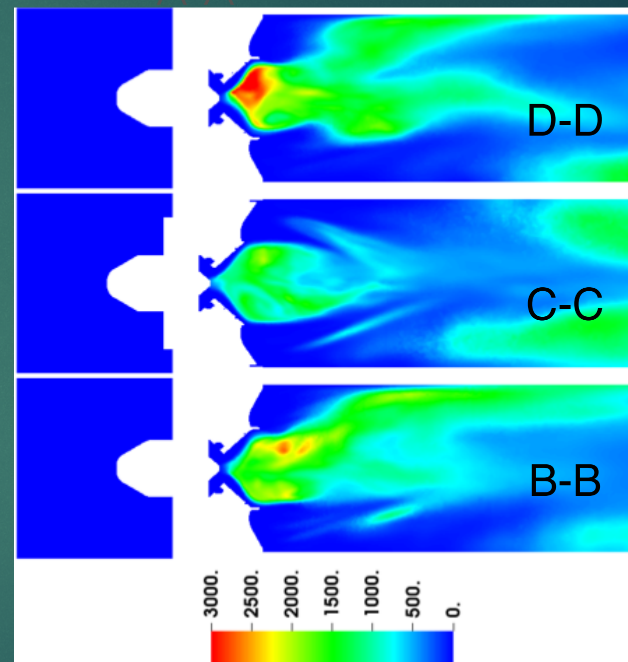
N+2 (Pilot Centerline)

A-A



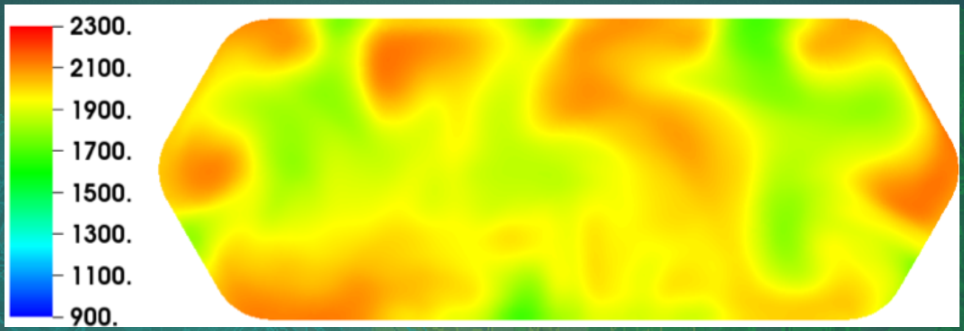
N+3

A-A

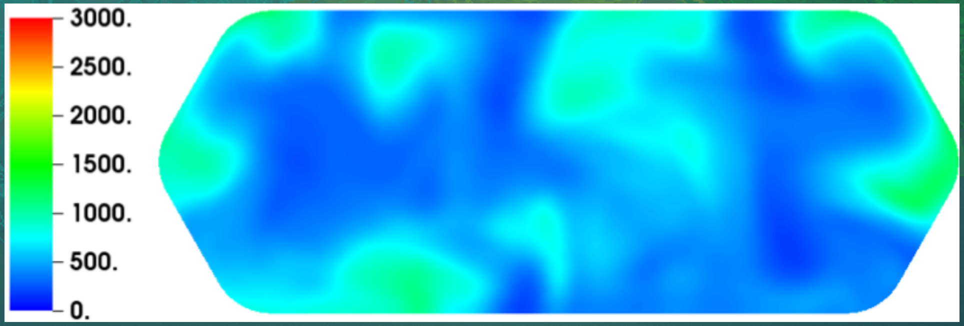


Pilot dominates NOx production in both configurations
N+3 Pilot regions have lower NOx than N+2 Pilot.
Overall NOx is similar for N+2 and N+3

Exit Plane Temperature and NO mass-fraction(*1e6) - N+3

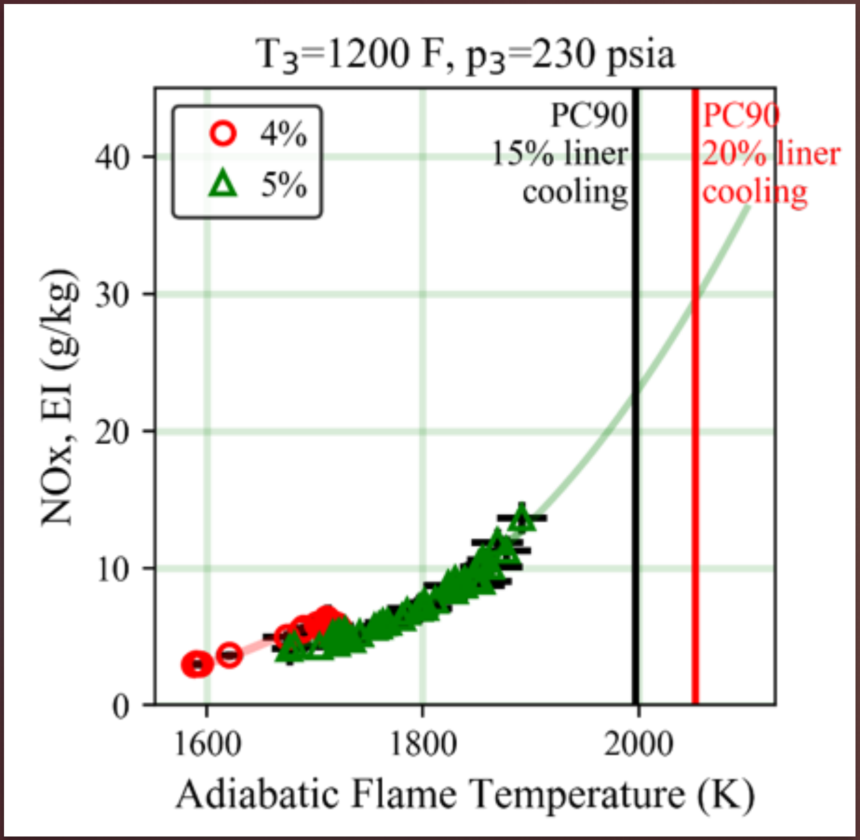


Temperature (K)



NO mass-fraction (*1e6)

CFD vs Experiment Comparison NO mass-fraction - N+3



PC90	Experiment	OpenNCC CFD
20% Liner Cooling	30	34
15% Liner Cooling	23	26

[Tacina 2017] Tacina, K.M., Podboy, D.P., Lee, P., and Dam, B., "Gaseous Emissions Results from a Three-Cup Flametube Test of a Third-Generation Lean Direct Injection Combustor Concept", ISABE 2017, Manchester UK.

Summary and Recommendations

- CFD analysis of a N+2 and N+3 flametube arrays performed with OpenNCC for Supersonic Cruise conditions
- EINOx predictions for the N+2 and N+3 conditions are fairly similar to each other
- CFD predictions of EINOx for the N+3 configuration match experimental data to within 15% accuracy

- Future work will focus on approaches to reduce cruise EINOx to the 5-15 range. The proposed strategies are:
  - Design of high-temperature combustion liners (reduced cooling air)
  - Compostion controlled fuels (hydro-treated, alkane-only)
  - Redesign injectors optimized for subsonic goals to optimize emissions for supersonics goals

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